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Assessment of revetment performance against wave overtopping for mitigating tidal flooding at Lebih Beach

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Abstract

As one of the largest archipelagic nations, Indonesia faces significant coastal erosion challenges, particularly in Gianyar Regency, Bali, where coastline change rates have reached -11.12 m/year. To combat this issue, the Indonesian government has implemented revetment structures along the coastline, notably at Lebih Beach. This research systematically assesses the current performance of a coastal revetment structure on Lebih Beach, focusing on its ability to withstand modern wave conditions and prevent wave overtopping. The objective is to evaluate the structure's physical integrity and functionality, especially as wave overtopping has impacted nearby communities and damaged infrastructure. The methodological framework incorporates detailed field surveys to document structural conditions and detect signs of erosion, material degradation, or damage. Topographic and bathymetric data are used to model the coastal and seabed profile, which is essential for simulating wave behavior. Wind, tide, and wave data from CMS-Wave in SMS 10.1 software provide insights into wave height, direction, and energy, helping predict wave impacts on each segment of the coastline. The research area is divided into six segments along the Lebih Beach coastline. Initial evaluations showed that segments 1 through 4 require further analysis due to evident vulnerabilities to wave forces. The reexamination compares the peak elevation of these segments, specifically their ability to withstand wave action at the established elevation of +5.00 m. This comparison allows for an accurate assessment of the structure's resilience under current environmental pressures and guides recommendations for maintenance or reinforcement where needed. The evaluation results in segments 1, 2, 3, and 4 showed that the revetment still undergoes overtopping. Continuous monitoring and evaluation of coastal protection structures is needed to ensure the integrity of coastal communities and infrastructure in the face of ongoing environmental changes.

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INTRODUCTION

Indonesia, recognized as one of the largest archipelagic nations globally, comprises approximately 17,504 islands, encompassing a maritime area of about 6,400,000 km² and a coastline extending 108,000 km [1][2]. Omara highlights Indonesia's scale of coastal challenges, emphasizing its vast naval territory and extensive coastline, underscoring the critical need for robust coastal protection measures [1]. Bali, with a coastline measuring 633 km [3] as one of Indonesia's provinces, has complex coastal dynamics, where dynamic forces such as wave action, tidal currents, and sediment transport continuously influence the coastal morphology [4]. These processes contribute to shoreline erosion, sediment redistribution, and the formation of vital coastal features, including beaches, dunes, and barriers. Understanding these dynamic forces is essential to mitigating coastal hazards and designing adequate infrastructure.

The studies conducted by Suhendra et al. from 2015 until 2020 showed that Gianyar Regency, one of Bali’s regencies, experiences a coastline change rate of -11.12 m/year [5]. In 2011, the Gianyar Regency government built a revetment in Lebih Beach as a coastal protection [6]. Revetments are sloping structures designed to protect coastal slopes from erosive forces, thus playing a crucial role in the management of shoreline integrity [7]. Studies conducted by Shrestha et al. show that these coastal protection infrastructures prevent erosion and substantially benefit the economy, public health, safety, and community well-being. In both riverine and coastal environments, revetments are essential in defending against flood events and storm-induced wave action, highlighting their significance in coastal engineering practices [8].

Severe coastal flooding occurred at Lebih Beach in 2019 and 2022, resulting in substantial wave overtopping of the revetment structures [9][10]. Wave overtopping is water overflow beyond the crest of coastal protective structures, primarily due to wave run-up [11]. Multiple factors can influence coastal flooding, particularly in coastal regions, including shoreline geometry, sea level rise, wave climate dynamics, and climate change-related impacts [10, 11, 12]. The structural integrity of revetments may be compromised if the crest height is inadequately designed, leading to excessive overtopping that adversely affects both the top and the rear side of these structures [15]. The consequences of wave overtopping can manifest under three scenarios: (1) when water levels exceed the crest elevation of the structure, (2) when waves surge over the crest, and (3) when the coastal structure is breached or otherwise compromised [14][15]. At Lebih Beach, wave overtopping disrupted local community activities, detached the revetment's armor layer, and damaged adjacent pedestrian pathways.

The issue of wave overtopping has attracted significant academic interest, prompting extensive investigations through various methodologies, including the multitude of methodologies explored by Kreyenschulte et al. [18], Vieira et al. [19], and others present a robust foundation for understanding wave overtopping. However, while theoretical and experimental studies provide valuable insights, a comprehensive synthesis of these approaches could yield more effective predictive models. The experimental work by Capel [20] illustrates the complexities of wave interactions with coastal structures. However, these studies often lack long-term data that could enhance their applicability to real-world scenarios.

As discussed by Alcérreca-Huerta and Oumeraci [21] and Cao et al. [22], the integration of numerical modeling techniques represents a significant advancement in the field. However, the potential for model calibration using local conditions at Lebih Beach is often overlooked. Such calibration could significantly improve the accuracy of predictions regarding wave overtopping and structural integrity, aligning with the findings of Jin et al. [15] regarding the critical role of revetment crest height.

Despite significant progress in understanding coastal protection in the form of revetments and wave overflows, there is still an alarming level of erosion in Gianyar Regency. This is exacerbated by climate change causing tidal flooding and the absence of a comprehensive evaluation of the performance of existing embankment structures in a specific context such as Lebih Beach, as shown in Figure 1.

This research addresses the critical need to evaluate the revetment's structural performance and functional adequacy at Lebih Beach, Gianyar Regency, Bali, in response to significant coastal erosion and wave overtopping. The construction sector is crucial in driving the national economy [23]. However, despite constructing a revetment in 2011 as a coastal defense measure, severe events overtopping 2019 and 2022 have highlighted potential deficiencies in its design, particularly the crest elevation. These deficiencies have compromised the revetment's ability to withstand high-energy wave run-up, resulting in structural instability, detachment of the armor layer, and damage to adjacent pathways.

This research evaluates the performance of the existing revetment structure at Lebih Beach against contemporary wave conditions, focusing on its physical and functional effectiveness in mitigating wave overtopping.

Figure 1. Tidal flood in Lebih Beach in 2022

Each year, the risk of overtopping waves poses significant threats, leading to diverse ecological disturbances and social impacts, including habitat loss, coastal erosion, infrastructure damage, and displacement of communities [24]. This research assesses the revetment's adequacy in safeguarding the coastline and recommends requisite adjustments or enhancements. A novel methodological approach will be employed, integrating structural evaluation results from field surveys with comprehensive wave hydraulic analyses utilizing the CMS-Wave model in SMS 10.1. This dual methodology will facilitate the determination of the optimal revetment height necessary to mitigate wave overtopping and coastal flooding effectively.

METHOD

Research Location

Lebih Beach is located in Lebih village, Gianyar Regency, Bali, Indonesia. The research location is from $8^{o}34^{'}39.45^{"}$ LS and $8^{o}34^{'}39.45^{"}$ E until $8^{o}35^{'}0.46^{"}$ LS and $115^{o}21'1.31$ E. The coastline was divided into six segments because the revetment structure in each segment has different conditions, as shown in Figure 2.

Research Data

This research's primary data collection involves surveying to gather preliminary information on the revetment structure and the surrounding coastal environment. This survey aims to identify critical issues impacting the structure, including erosion, wave overtopping, and any visible structural damage that may need immediate attention. By assessing these physical conditions, the survey provides a foundation for understanding potential weaknesses in the revetment and identifying areas where improvements or repairs may be necessary.

Secondary data in this study further supports the research by offering a broader context on environmental conditions and historical trends. This data includes: (1) the current condition of the existing revetment, which provides insight into the structure's resilience and performance over time; (2) topographic and bathymetric maps, essential for understanding the coastal terrain and seabed profile, which influence wave behavior and sediment transport; (3) wind data from 2014 to 2023, which helps analyze long-term wind patterns that contribute to coastal erosion and wave generation; (4) tidal data, necessary for understanding water level variations that affect wave action on the revetment; and (5) a map of Bali Island, providing a geographical reference for situating the study area within the larger coastal environment. This combination of primary and secondary data creates a comprehensive understanding of the revetment's current state and the environmental forces that shape its performance, enabling well-informed recommendations for coastal protection.

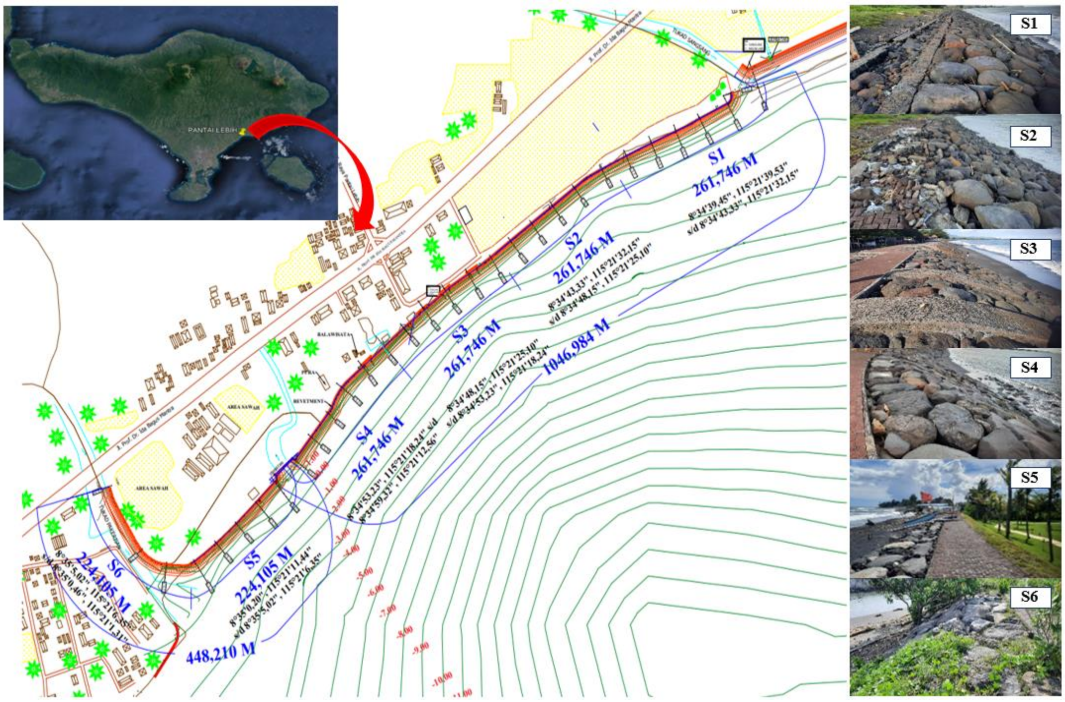

Figure 2. Research the location and conditions of each segment.

Methods

Figure 3 illustrates the methodology for evaluating a coastal revetment structure's physical and functional performance. This detailed and systematic approach integrates field-based observations and advanced data analysis techniques.

The process begins with the study's initiation, where an initial survey is conducted to gather preliminary information about the revetment structure and the surrounding coastal environment. This survey helps to identify critical issues such as erosion, wave overtopping, and any visible structural damage that may need to be addressed.

Following the survey, the next step is problem identification, where the specific challenges related to the revetment structure are clearly defined. This could include problems like severe erosion at the toe of the structure, frequent wave overtopping events, or signs of structural fatigue or failure. Identifying these problems sets the stage for targeted data collection and analysis The primary data is gathered through on-site documentation and field surveys focusing on the revetment's physical condition. This involves detailed inspections of the revetment's structure, including the armor layer, slope stability, signs of material degradation, and any visible structural damage. Photographs, measurements, and detailed notes are taken to document the structure's current state.

This primary data is then used to evaluate the revetment's physical condition and functional performance. The evaluation seeks to determine whether the revetment protects the coastline from erosion and wave overtopping and whether it is in good structural condition. A comprehensive map of Bali Island is obtained, which includes geographical features, land use patterns, population density, and the location of the revetment and other critical coastal infrastructure. This map provides context for the study and helps understand the broader coastal dynamics.

Meteorological stations collect wind data from 2014 to 2023. This dataset includes information on wind speed, direction, and variability, which is crucial for understanding the generation and direction of waves that impact the revetment. Topographic and Bathymetric Maps provide detailed information on the elevation of the land and underwater topography around the revetment. Topographic maps show the shape and features of the coastal landscape, while bathymetric maps illustrate the depth and contours of the seabed. These are essential for modeling how waves approach and interact with the revetment.

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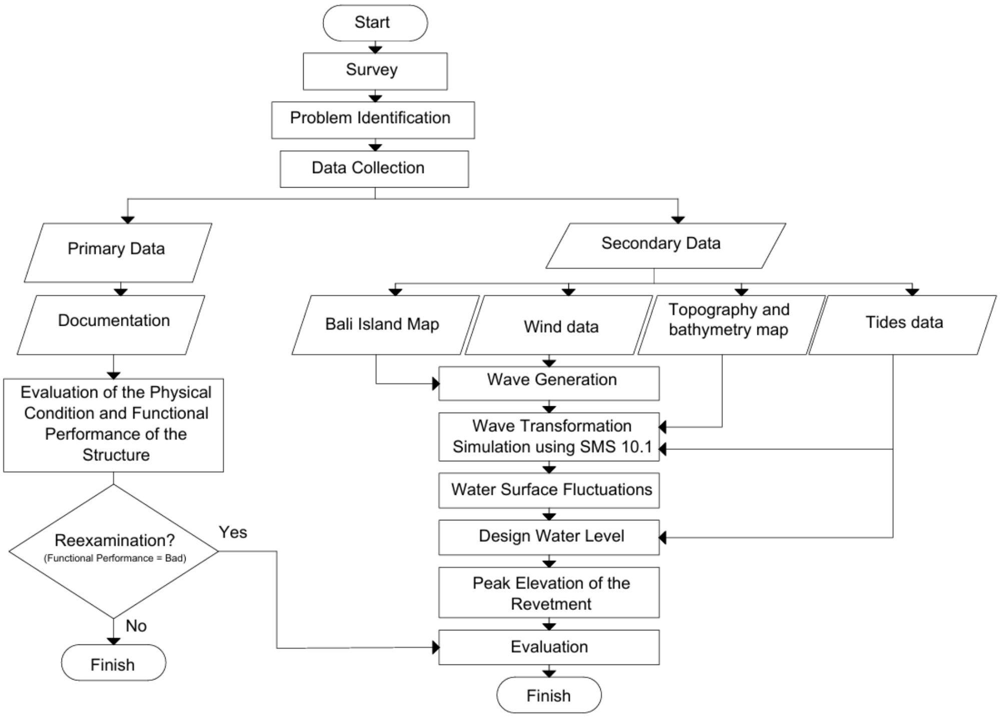

Figure 3. Flowchart of the research

Tidal data is collected to understand the sea-level variations over time, including the timing and magnitude of high and low tides. This data helps assess how tidal fluctuations contribute to wave overtopping and the overall stress on the revetment. With the collected secondary data, the next phase involves Wave Generation modeling. This step uses the wind, topographic, bathymetric, and tidal data to simulate the waves the revetment will likely encounter. The wave generation model predicts waves' height, direction, and energy as they approach the shoreline.

Subsequently, current waves were simulated using SMS 10.1 to create wave transformations. Data that needed input in the simulation were topography and bathymetry maps, tide data, wave direction, significant wave height, and significant wave period. The data output from the wave transformation simulation is the wave height at the existing revetment location that will be used to calculate run-up. The results of the run-up calculation are used as one of the parameters for calculating the peak elevation of the revetment, along with the design water level and freeboard parameters. The evaluation results of the reexamined segments were obtained by comparing the current wave analysis's peak elevation revetment with the existing peak elevation revetment, which was +5.00 m.

After the proposed adjustments were implemented, the final evaluation focused on confirming the revised structural adequacy and functional performance of the Lebih Beach revetment. This stage would typically involve several vital assessments. First, a hydraulic performance assessment using the CMS-Wave model in SMS 10.1 was likely employed to simulate current wave conditions and predict overtopping rates, ensuring the revised structure effectively prevents wave overtopping. A structural condition inspection would also be essential to verify the revetment's physical stability, durability, and integrity after adjustments, often conducted through field surveys or direct measurements. This ensures that the modifications address overtopping and maintain the structure's resilience over time. A functional performance review would follow, checking if the adjusted revetment meets the intended coastal protection objectives without frequent overtopping based on observational or monitoring data.

Evaluation of the Physical Condition and Functional Performance of the Structure

Evaluation of the structure's physical condition and functional performance includes physical component index calculation, component values calculation, index condition value calculation, and functional performance of the structure assessment [25].

A value called the structure condition index indicates the physical condition of the structure. The value is determined by entering condition component index values from indicators observed and recorded during the survey. In the context of the coastal structure, a value scale from 1 to 4 is used to calculate the physical component index. A value of 1 indicates the best condition, while a value of 4 indicates the worst condition of each part of the coastal structure [25].

Subsequently, component values are calculated using (1).

$$\text{Component value} = \text{index value x weight} \qquad (1)$$

The weight of the physical component of the structure is different according to the type of coastal structure that will be evaluated, as shown in Table 1 [25]. After calculating the component index, calculate the index condition value using (2) [25].

$$\text{Index condition} = \frac{\sum \text{Component value}}{\sum \text{Weight}} \qquad (2)$$

Functional performance values can be variable but simplified to “Good” or “Bad,” as shown in Table 2 [25]. The action advice is based on the structure's index value and functional performance, as shown in Table 3 [25].

Table 1. Weight of the physical component of the structure

Type of Structure	**Weight of the Physical Component**			
	Peak	**Body**	**Foundation**	**Material**
Revetment	30	20	10	40
Scalloped Revetment	10	30	20	40
Seawall	20	10	30	40
Retaining wall	10	10	40	40
Breakwater	20	20	20	40
Groin	10	10	40	40
Jetty	10	10	40	40

Table 2. Structure Function Performance

Protected Object	Structure Function Performance	
	Good	**Bad**
Outer Island	The beach does not erode or may even widen. The coastline can recede at times but advance again, maintaining a balance throughout the year.	The coastline consistently recedes over time. Trees along the shore topple, and some roots are exposed due to water erosion.
National Road/ Province Road/ District Road/City	The road is intact and stable. However, it could be covered by sand thrown by large tidal waves, extending far behind the structure.	Cracks appear due to the disturbed road foundation. The road experiences sinking or subsidence. The road shoulders appear eroded and are getting closer to the roadbed.
Settlement Area	The settlement is safe from wave threats. Dunes can form along the coastline.	Waves affect the settlement. As the coastline advances closer to the residential areas, breaking waves reach the houses closest to the beach.
Tourist Area	The tourist area is safe from wave disturbances. On steep beaches, coastline walls are not eroded, and cliff collapses no longer occur. On wide sandy beaches, the shoreline is maintained or even expanded.	Wave energy and waves still disturb the tourist area. Erosion and cliff collapse still occur on steep beaches. On sandy beaches, the amount of sand is decreasing, and the width of the beach is shrinking, making the tourist area increasingly narrow.
Public/Social Facilities	Public facilities are in safe and operational condition. The wave height reaching the location does not exceed the planned estimates, thus not disrupting activities.	The coastal structures are unable to improve the situation. The size of the incoming wave disrupts activities at the facility, and the facilities may even suffer damage due to the waves.

Wave generation

The wind stress factor (UA), effective fetch, and duration of sea wind speed were required to determine the wave height [26].

The wind speeds in different directions are plotted into a Windrose diagram, as shown in Figure 4 [27]. The wind data and analysis were utilized to forecast the wave [28].

Wind-stress factor (U_A) is calculated using (3) [29].

$$U_A \;=\; 0.71\,{U_w}^{123} \tag{3}$$

Where:

U_A = wind speed correction (m/s)
U_W = wind speed at sea (m/s)

Fetch is the length of the area where the wind blows with constant speed and direction that can generate a wave [26]. Effective fetch is calculated using (4) [29].

$$Feff = \frac{\sum x_i \cos\alpha}{\sum \cos\alpha} \tag{4}$$

Where:

Feff = effective fetch length
X_i = fetch length on each segment
α = deviation on both sides from the wind direction, by adding 6°- 42° on both sides from the wind direction.

Significant wave height and wave period are calculated using (5) and (6) [29].

$$Hs = \;0.0016\,x\sqrt{\frac{gFeff}{{U_A}^2}}\,x\,\frac{{U_A}^2}{g} \tag{5}$$

$$Ts = \;0.2857\,x\left(\frac{gFeff}{{U_A}^2}\right)^{\frac{1}{3}} x\,\frac{U_A}{g} \tag{6}$$

Where:

Hs = significant wave height (m)
Ts = significant wave period (s)
U_A = wind speed correction (m/s)
Feff = effective fetch (m)
g = earth gravity acceleration (9.81 m/s^2)

The return wave is calculated using the Gumbel method, which uses (7) and (8).

$$H_t \;= \overline{Hs} + \frac{\sigma H}{\sigma n}(Y_t - Y_{\bar{n}}) \tag{7}$$

$$T_t = \;0.33x\sqrt{\frac{H_{25}}{0.0056}} \tag{8}$$

Table 3. Action advice

Functional Performance	Structure Physical Condition		Action Advice
	Index Value	**Condition**	
Good	0.0 < value ≤ 1.5	Good	Monitoring
	1.5 < value ≤ 2.5	Good Enough	Monitoring
	2.5 < value ≤ 3.5	Damaged	Maintenance
	>3.5	Heavily Damaged	Rehabilitation
Bad	0.0 < value ≤ 1.5	Good	Reexamination
	1.5 < value ≤ 2.5	Good Enough	
	2.5 < value ≤ 3.5	Damaged	
	>3.5	Heavily Damaged	

Where:
$\overline{Hs}$ = average wave height (m
σH = standard deviation
t = return period (year)
Y_t = Reduced variance as a function of the return period
$Y_{\bar{n}}$ = Reduced variance as a function of the amount of data (N)
σn = Reduced variance deviation as a function of the amount of data
H_t = wave height of the return period (m)
T_t = wave period of the return period (s).

Simulation of wave transformation using SMS 10.1

For the simulation, wave transformation was performed using the CMS-Wave model in SMS 10.1. The data to be input in the wave transformation simulation in SMS 10.1 are topographic and bathymetric contour data, wave height, wave period, dominant wave generation direction, and highest water level (HWL) [30]. The output of this simulation is the wave height at the existing revetment location, which is later used in the run-up calculation.

Water Surface Fluctuations

Water surface fluctuations include wave setup, wind setup, and sea level rise.

Wave setup is the time-averaged extra water level elevation caused by breaking waves [31]. It is calculated using (9) [29].

$$S_w = 0.19\left[1 - 2.82\sqrt{\frac{Hb}{gT^2}}\right]Hb \qquad (9)$$

Where :
Sw = wave setup (m)
T = wave period (s)
Hb = height of the wave breaking (m)
g = earth gravity acceleration (9.81 m/s^2)
Wind setup is calculated using (10) [29].

$$\Delta\text{h} = F_c\frac{V^2}{2gd} \qquad (10)$$

Where :
Δh = wind setup (m)
F = effective fetch length (m)
c = constant (3.5 x 10-6);
v = wind speed (m/s);
d = water depth (m)
g = earth gravity acceleration (9,81 m/s2)

Rising sea levels are still significantly influencing global coastal flood production [32]. Sea level rise is calculated using graphics, as shown in Figure 4 [29].

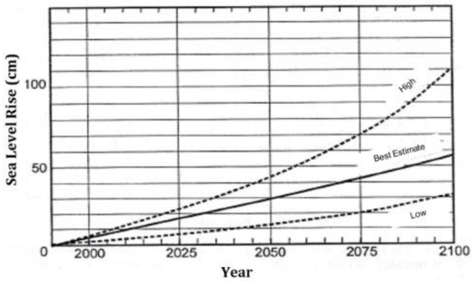

Figure 4. Sea level rise

Design Water Level (DWL)

The design water level was calculated using (11) [27][31] to guarantee that the revetment structure can endure the water pressure brought on by gradual variations in water levels, especially during floods or strong waves[29][33].

$$\text{DWL} = \text{HWL} + \Delta\text{h} + \text{Sw} + \text{SLR} \qquad (11)$$

Where:
DWL = design water level
Δh = wind setup (m)
SW = wave setup
SLR = sea level rise

Revetment Crest Elevation

Overtopping occurs when the run-up at the structure is higher than the crest freeboard. [34]. The run-up is calculated using (12) [35].

$$\text{Ir} = \frac{tg\theta}{\left(\frac{H}{L_0}\right)^{0,5}} \qquad (12)$$

Where:
Ir = Irribaren number
θ_r = slope
H = wave height at the structure (m)
L0 = wavelength at the deep sea (m).

The crest elevation of the revetment structure was calculated using (13) [29].

$$\text{El}_{\text{revetment}} = \text{DWL} + \text{Ru} + \text{Fb} \qquad (13)$$

Where:
DWL = design water level (m)
Ru = run-up (m)
Fb = freeboard (0.5 – 1.0 m)

RESULTS AND DISCUSSION

Result of the Evaluation of the Physical Condition and Functional Performance of the Structure

An on-site survey has evaluated the current revetment structure at Lebih Beach for its functional performance and physical state. The value of the physical component index is based on the physical condition of each part of the revetment structure. Then, the component value is calculated using (1), as shown in Table 4.

Subsequently, the index condition value was calculated using (2), as shown in Table 5, and the functional performance results, as shown in Table 6, were specified accordingly in Table 2. After that, the action advice results in every segment, as shown in Table 7, were specified accordingly in Table 3 [25].

Table 4 provides a detailed assessment of the physical condition of various segments (S1 to S6) of a revetment structure, focusing on four key components: the crest, body, foundation, and material. The index values, which range from 1 to 4, indicate the condition of each component, with 4 representing the poorest state and 1 representing the best. Segment S2 is in the most critical condition, with the highest index value of 4 for several components (Crest, Body, and Material), indicating that it is Heavily Damaged. As a result, rehabilitation is recommended for this segment to restore its functionality. Segment S1 has a maximum index value of 3 in the Material component, classifying it as Damaged and needing maintenance to prevent further deterioration. Segments S3, S4, S5, and S6 show lower index values across all components, with maximum values of 1 or 2. This suggests that these segments are in Good or Good Enough condition, requiring only routine monitoring to ensure their continued stability and performance.

Table 5 is a detailed evaluation of the structural condition of different segments (S1 to S6) of a revetment structure, focusing on four key components: the crest, body, foundation, and material. Each component is assigned a specific value, reflecting its condition within each segment. These values are then summed to provide a total component value for each segment, subsequently used to calculate an index condition value.

Table 5 evaluates the condition of six segments, where one index represents the best condition and four the worst. Segments S3, S5, and S6, each with an Index Condition Value of 1.0, are in the best condition, indicating they are well-maintained and require minimal to no immediate repairs. Segment S4, with an index of 1.5, is in good condition, though not perfect, suggesting it may need only minor maintenance. Segment S1 has an Index Condition Value of 2.4, placing it in a fair condition; while generally functional, it could benefit from some targeted improvements. Finally, Segment S2, with an index of 3.9, is in the poorest condition, close to the maximum index value of 4. This indicates that S2 may need significant repair or renovation to restore it to a satisfactory state. Overall, the table highlights that S3, S5, and S6 are in optimal condition, whereas S2 requires the most attention to improve its structural integrity.

Table 6 presents the functional performances of different segments of a coastal protection structure, explicitly focusing on their ability to prevent overtopping during tidal events.

Table 4. The physical component index of each segment

Segment	**Physical Component Index Value**			
	Crest	**Body**	**Foundation**	**Material**
S1	1	2	1	3
S2	4	4	2	4
S3	1	1	1	1
S4	1	2	2	1
S5	1	1	1	1
S6	1	1	1	1

Table 5. The component value and index component value of each segment

Segment	**Component Value**				**Total**	**Index Condition Value**
	Crest	**Body**	**Foundation**	**Material**		
S1	30	40	10	120	480	2.4
S2	120	80	20	160	1480	3.9
S3	30	20	10	40	100	1.0
S4	30	40	20	40	190	1.5
S5	30	20	10	40	100	1.0
S6	30	20	10	40	100	1.0

Table 6. Functional Performances of each segment

Segment	Functional Performance		
	Protected object	Description	Function Performance
S1	Tourist area	Overtopping	Bad
S2	Tourist area	Overtopping	Bad
S3	Tourist area and public/social facilities	Overtopping	Bad
S4	Tourist area and public/social facilities	Overtopping	Bad
S5	Tourist area	Non-overtopping	Good
S6	Tourist area	Non-overtopping	Good

Table 7. Recapitulation of the evaluation of the physical condition and functional performance

Segment	Physical Structure		Functional Performance	Action Advice
	Index Value	Condition		
S1	2.0	Good enough	Bad	Reexamination
S2	3.8	Heavily damaged	Bad	Reexamination
S3	1.0	Good	Bad	Reexamination
S4	1.3	Good	Bad	Reexamination
S5	1.0	Good	Good	Monitoring
S6	1.0	Good	Good	Monitoring

Segments S1, S2, S3, and S4 are all located in areas with significant tourist and public/social facilities, and they are reported to have poor performance due to overtopping, indicating that these segments are failing to adequately protect the areas they serve from flooding and wave impacts. In contrast, Segment S5, which also serves a tourist area, has demonstrated exemplary performance by effectively preventing overtopping, highlighting its reliability in safeguarding the designated location. This disparity in performance among the segments suggests an urgent need for improvements in the segments experiencing overtopping to ensure adequate protection for tourists and public facilities.

Based on Table 7's result, segments 1, 2, 3, and 4 needed reexamining against current waves, and segments 5 and 6 needed monitoring.

Wave analysis results

Wave analysis starts with making a windrose that contains wind speed in all directions at Lebih Beach. Figure 5 shows the sequence of presentations of winds at Lebih Beach. The dominant wind direction is from the southeast (42.86%). Subsequently, the wind speed correction (U_A) was analyzed using dominant wind data and using (3), as shown in Table 11 [36].

The Fetch line is drawn at intervals of every 6˚- 42˚[26]. The fetch length is assumed to be 1000 km if not encountering land [37]. Effective fetch is calculated using (4) in the southeast direction according to the dominant wind direction, as shown in Figure 6.

$$Feff = \frac{\sum x_i \cos\alpha}{\sum \cos\alpha} = \frac{4612.257\ \text{km}}{13.511} = 341.373\ \text{km}$$

After that, the significant wave height of each year was calculated using (5), and the maximal significant period wave of each year was calculated using (6), with results as shown in Table 8. Subsequently, the return wave was calculated using the Gumbel method, as shown in Table 9.

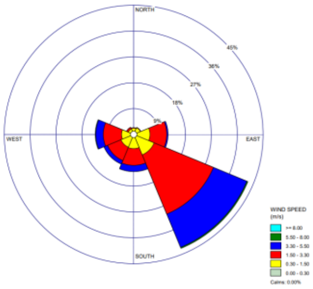

Figure 5. The wind rose at Lebih Beach.

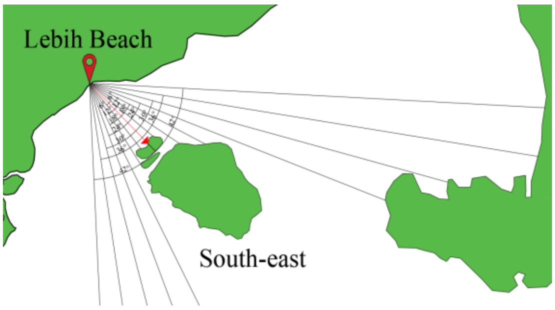

Figure 6. Fetch in Lebih Beach

Table 8. Significant wave height and duration (2014-2023)

Year	Ua (m/s)	Direction	Feff (m)	Hs_{max} (m)	Ts_{max} (s)
2014	10.584	SE	341372.6	3.159	9.567
2015	9.632	SE	341372.6	2.875	9.271
2016	9.145	SE	341372.6	2.730	9.112
2017	10.407	SE	341372.6	3.106	9.513
2018	9.946	SE	341372.6	2.969	9.370
2019	10.802	SE	341372.6	3.224	9.632
2020	11.457	SE	341372.6	3.420	9.823
2021	8.899	SE	341372.6	2.656	9.029
2022	11.200	SE	341372.6	3.343	9.749
2023	11.433	SE	341372.6	3.412	9.816

Table 9. Wave height and wave duration of the return period

No	Return Period (Year)	Hs (m)	Ts (m)
1	2	3.079	7.738
2	5	3.170	7.851
3	10	3.230	7.926
4	25	3.314	8.028
5	50	3.363	8.086
6	100	3.419	8.154

The height and duration of the plan used are 25 years, with Hs = 3.314 m and Ts = 8.028 s.

Simulation of Wave Transformation Results

To simulate current wave transformation, data such as the topography and bathymetry contour of Lebih Beach, the highest water level at Gianyar Regency (HWL = +2.795 m), wave height (H25 = 3.314 m), wave duration (T25 = 8.028 s), and wind direction (southeast) are required [30].

As shown in Figure 7, an observation line is drawn on each segment to determine the wave transformation. The distance of the existing revetment from the starting point of each observation line must be measured to get the wave height at the revetment location. Figure 8 is the resulting model of the wave transformation at Lebih Beach using the CMS-Wave model. Subsequently, the wave height used for run-up analysis is at the distance of the existing revetment location because the wave height parameter results are based on the particular distance. Table 10 shows the wave height at the existing revetment based on the wave transformation results from Figure 8.

The wave height at the existing revetment location will be used to calculate run-up using (12), as shown in Table 12.

Evaluation results

The parameter to be evaluated was the elevation of the revetment crest. The elevation of the revetment crest was calculated using the design water level, run-up, and freeboard parameters. The design water level was calculated using (11); the result is shown in Table 11. The evaluation was carried out by comparing the crest elevation of the existing revetment (+5.00 m) with reexamination results in each segment. Based on Table 13, segments 1, 2, 3, and 4 are still overtopping because the reexamination crest elevation result is more significant than the existing one.

Table 10. Wave height at the revetment location

No	Segment	H (m)
1	S1	1.249
2	S2	1.694
3	S3	1.148
4	S4	1.140

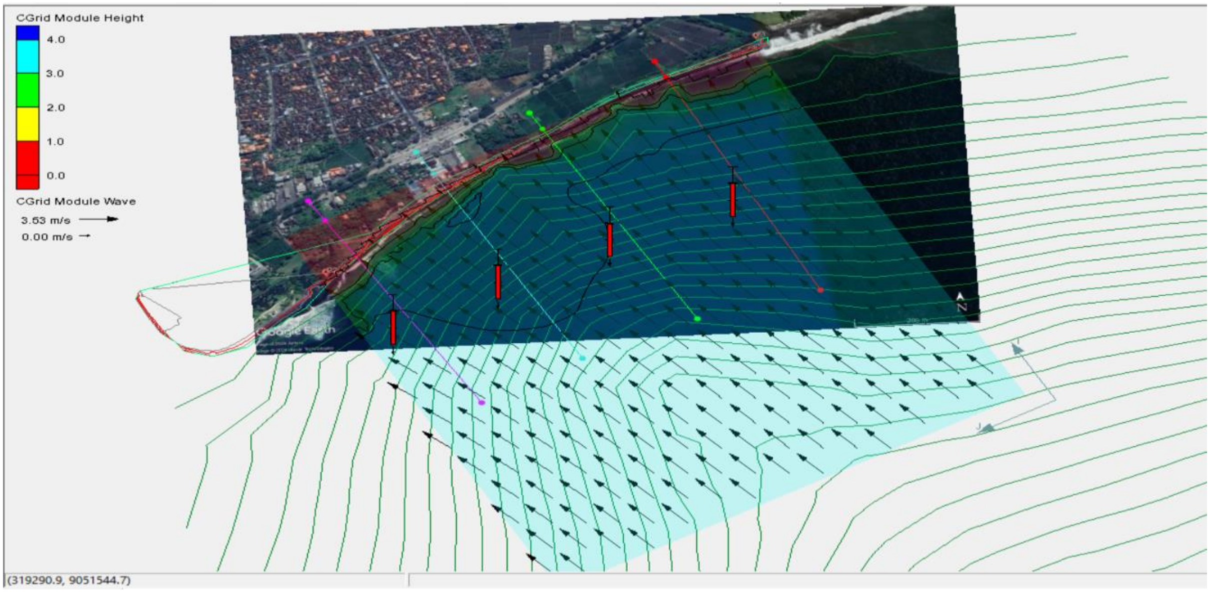

Figure 7. Observation line on each segment

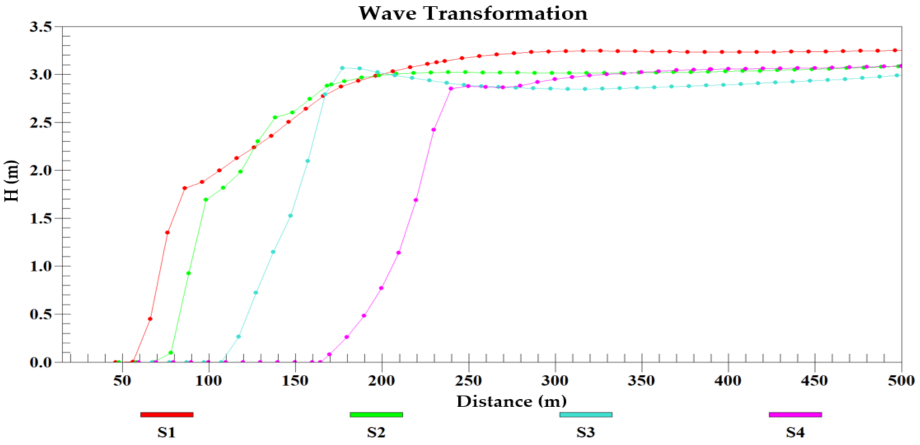

Figure 8. Wave transformation on each segment

Table 11. Design water level

No	Parameter	Value (m)
1	Highest water level	2.795
2	Wind setup	0.165
3	Wave setup	0.536
4	Sea level rise	0.12
	DWL (HWL+S_w+Δh+SLR)	**3.616**

Table 12. Peak elevation of the revetment of each segment

Segment	DWL	H	Ru	Fb	$El_{revetment}$
	(m)	(m)	(m)	(m)	(m)
S1	3.616	1.249	1.549	0.5	+5.666
S2	3.616	1.694	1.990	0.5	+6.107
S3	3.616	1.148	1.424	0.5	+5.540
S4	3.616	1.140	1.425	0.5	+5.541

The Crest elevation of the revetment was calculated using (13), and the result is shown in Table 12.

Table 13. Evaluation results

Segment	Peak Elevation of the Revetment (m)		Result
	Existing	Reexamination	
S1	+5.000	+5.666	Overtopping
S2	+5.000	+6.107	Overtopping
S3	+5.000	+5.540	Overtopping
S4	+5.000	+5.541	Overtopping

Several strategies can be implemented to mitigate the issue of tidal flooding and wave overtopping in the existing revetment where the crest elevation is insufficient. The most direct solution is to raise the crest height of the revetment to meet or exceed the reexamined required elevation, potentially in phases if budget constraints exist [38]. Additionally, reinforcing the revetment with wave return walls or more robust armour layers can help reduce overtopping by deflecting waves and absorbing more energy. Additional coastal structures, such as seawalls, bulkheads, or offshore breakwaters, can reduce wave energy before it reaches the shore. Improving drainage systems and constructing overflow channels behind the revetment will help manage any water that overtops the structure [39].

Planting salt-tolerant vegetation or enhancing the beach before the revetment can act as a Natural defense and buffer against waves. Regular monitoring and maintenance of the revetment are crucial for ensuring its long-term effectiveness. At the same time, advanced engineering solutions, including numerical modeling and adaptive management, can optimize the design and response to changing conditions [38, 39, 40].

CONCLUSION

The evaluation of the revetment structure at Lebih Beach focused on assessing its physical and functional performance across different segments. Key components, including the crest, body, foundation, and material, were analyzed, revealing that Segment S2 is in the most critical condition, marked by heavy damage and necessitating immediate rehabilitation. Segment S1, while showing signs of deterioration, requires maintenance to prevent further issues. In contrast, segments S3, S4, S5, and S6 are in good to fair condition, only needing routine monitoring. Functional performance assessments indicate that segments S1, S2, S3, and S4 are ineffective in preventing overtopping, compromising their protective function, particularly for tourist and public areas. However, segments S5 and S6 perform well, effectively preventing overtopping.

The wave analysis at Lebih Beach, which considers wind and wave conditions, shows that the dominant wind direction is from the southeast. Wave heights from 2014 to 2023 ranged between 2.656 m and 3.420 m, with a plan period of 25 years aligning with a significant wave height of 3.314 m and a period of 8.028 seconds. These wave parameters are essential for understanding the forces impacting the revetment structure and planning necessary improvements. Simulations of wave transformation further highlight wave height variations across segments, with Segment S2 experiencing the highest wave impacts, potentially contributing to its overtopping issues.

In evaluating the crest elevation of the revetment, a comparison between current and reexamined elevation requirements revealed overtopping problems in segments S1, S2, S3, and S4. The reexamined crest elevation for these segments exceeds the existing level, indicating a need for elevation adjustments to mitigate overtopping. Recommendations for improvement include raising the revetment crest height, reinforcing the structure with wave return walls or stronger armour, and adding additional coastal defenses like seawalls or offshore breakwaters. Other strategies, such as enhancing drainage systems, constructing overflow channels, and planting salt-tolerant vegetation, could provide natural buffers. Routine monitoring, advanced engineering solutions, and adaptive management will ensure the revetment's long-term effectiveness in protecting the coastal area.

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